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Simplified Model for FEM Simulation of SAW Delay Line Sensor

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Abstract

Surface acoustic wave (SAW) devices can be modeled using various methods such as equivalent circuit model, coupling of modes method and finite element method (FEM). FEM simulation of SAW devices serves to optimize SAW structures and allows getting insight physics of propagation of SAW over the substrate. In most of the earlier work on FEM simulation of SAW sensors, entire device structure is considered for the simulation and the number of degrees of freedom (DOF) to solve is significantly high. Thus it is important to identify valid approximation and simplified models to reduce the computational cost. In this paper a 2D-finite FEM simulation of SAW delay line model using COMSOL Multiphysics (commercial FEM software) is discussed. We have modeled a Rayleigh wave type SAW device choosing YZ Lithium Niobate as the substrate. The major contribution of this work is the application of periodic boundaries to the transmitter interdigital transducer (IDT) to reduce the number of degrees of freedom of a SAW delay line model solution. The simulation methodology and time domain response of the model are discussed.

Keywords: Nano-pillars;SAW Sensor; MEMS; Microresonant Sensor Simulation;

Nomenclature

u, u_a, u_b	Displacement vectors (m)
N_M	number of force generators
F_n	Force (N)
V_{in}	Input voltage
v	Velocity of SAW
λ	Wavelength of SAW

1. Introduction

Surface acoustic wave (SAW) devices based on various types of acoustic waves such as Rayleigh wave, Shear-SAW, Love wave, acoustic plate mode (APM) and flexural plate wave (FPM) have been explored for sensors, actuators and telecommunication applications. Figure 1 shows a typical SAW delay line sensor. It consists of transmitting interdigital transducer (IDT) and receiving IDT separated by delay line. The delay line is covered by sensing film. Changes in the properties and dimensions of the sensing material caused by a particular measurand introduces perturbations such as change in mass loading, conductivity, permittivity, viscosity, temperature, and strain over the acoustic path and alter the velocity, amplitude and phase of the SAW [1]. Early researchers rely on experiments to design and develop SAW devices. There

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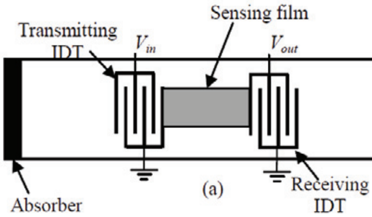


Fig. 1. A SAW delay line sensor

were frequent discrepancies in actual function of devices. Basic design of SAW transducers has to be optimized with the help of modeling techniques. Computer aided simulation such as a finite element method (FEM) simulation helps in designing SAW devices and studying the characteristics of these devices made on new piezoelectric substrates. Further FEM simulations of SAW devices help in estimating and visualizing the SAW device response before fabricating these devices. The following researchers have reported FEM simulation of SAW devices. Atashbar *et al*. [2] simulated mass loading effect of palladium sensing film in the presence of hydrogen. Wu *et al*. [3] used Taguchi method on FEM results and established robust design processes for SAW sensors based on the mass loading principle. Ippolito *et al*. [4] performed FEM analysis of acoustic waves propagating on layered SAW devices. Xu [5] has reported FEM simulation of a SAW filter. Subraminian *et al*. [6] used FEM simulation to design SAW device suitable in remotely readable micro accelerometers. We have also worked on FEM simulation of SAW sensors with resonant structures as sensing medium and studied their mass loading effects [7, 8]. In most of the earlier SAW delay line device simulations, complete SAW structures were considered for 2D or 3D FEM simulations, accordingly the number of degrees of freedom to solve is high. It is important to identify simplified SAW delay line model and valid approximations to reduce number of DOF to solve during an FEM simulation. In this paper we have proposed a simplified methodology to perform FEM simulation of SAW delay line devices within considerable number of DOF to solve during a time domain analysis. These improvements are based on the fact that the IDTs consist of repetitive identical electrodes (fingers) and the DOF of the solution can be minimized by considering a section of transmitting IDT and applying appropriate periodic boundary conditions to the boundaries of the section. The FEM simulations in the present work were carried out using COMSOL Multiphysics, commercial FEM software. The mathematical model of SAW delay line device, simulation methodology and results are briefed in the following sections.

2. Simulation Methodology

2.1 The mathematical model for a SAW delay line

The IDT converts electrical energy to mechanical energy and vice versa. The mathematical model of a SAW delay line given by Feng *et al*. [9] is adopted in this work for formulating the simplified SAW delay line model. The transmitting IDT can be considered as a force generator that converts electrical voltage to mechanical forces [9]. These forces travel as SAW on the piezoelectric substrate. Consider a transmitting IDT as shown in figure 2, with N_M number of force generators (finger pairs). If the force generated at each finger of transmitter IDT is proportional to the applied voltage, the force at n^{th} finger pair can be written as $F_n(t) = K_1\ V_{in}(t)$, where K_1 is proportionality constant of the transducer and V_{in} is the input voltage. The displacement of the wave u at the edge of IDT of N_M finger pair can be written as

$$\mathbf{u}(t) = \frac{1}{2v}\sum_{n=1}^{N_M} F_n\left(t - \frac{n\lambda}{v}\right) \tag{1}$$

where, t is time, λ is wavelength of SAW, and v is the SAW velocity
For instance, the displacement amplitude at edge of $n = m^{th}$ pair from equation (1) can be rewritten as

$$\mathbf{u}(t) = \frac{1}{2v}\sum_{n=1}^{n=m} F_n\left(t - \frac{n\lambda}{v}\right) - \frac{1}{2v}\sum_{n=m+1}^{n=N_M} F_n\left(t - \frac{n\lambda}{v}\right) \tag{2}$$

For a periodic IDT, the above equation can be re-written as

$$\mathbf{u}(t) = \underbrace{\frac{1}{2v}\sum_{n=1}^{n=m} F_n\left(t-\frac{n\lambda}{v}\right)_{\text{for all } t}}_{\mathbf{u}_a(t)} - \underbrace{\frac{1}{2v}\sum_{n=1}^{n=N_M-m} F_n\left(t-\frac{n\lambda}{v}\right)_{\text{for } t>=\frac{n\lambda}{v}}}_{\mathbf{u}_b(t)} \tag{3}$$

or simply,

$$\mathbf{u}(t) = \mathbf{u}_a(t) - \mathbf{u}_b(t) \tag{4}$$

The terms $\mathbf{u_a}(t)$ and $\mathbf{u_b}(t)$ in Eq.4 can be realized as two separate one-port SAW resonator consisting of IDT with N_m and N_M-m finger pairs. It is convenient to model a one-port SAW resonator using infinite periodic boundary condition [8]. Thus a transmitting IDT in the SAW delay line device can be modeled as a section of IDT in a one port SAW resonator of width λ and by providing appropriate periodic boundary conditions to the left and right side boundaries of the section [10]. The simulation procedure adopted in COMSOL Multiphysics to solve the SAW delay line model is explained in the following section.

2.2 Simulation procedure

YZ-Lithium Niobate piezoelectric crystal is assumed as the substrate in the simulations. The SAW delay line model considered for the simulation is shown in figure 3. The SAW delay line structure used in simulation consists of 3 sub domains, the transmitter IDT ($G1$) to generate the Rayleigh waves, delay line of length l ($G2$) and the delay line is extended as $G3$ to absorb propagating SAW and avoid reflections back to the IDT. In the simulation a transmitting IDT consisting of two electrodes of each having a width of 8.75 μm (λ/4) and a delay line of 69.76 μm (2 λ) is considered. Following boundary conditions are set to $G1$ to simulate a transmitting IDT of 5 finger pairs (m = 5). The degrees of freedom of the right periodic boundary (Γ_R) are set to be equal of those from the left periodic boundary (Γ_L) (see figure 3) and the displacement boundary conditions for the Γ_R boundary is set to satisfy the displacement $\mathbf{u}(t)$ in the Eq. 3. Critical damping is assumed to the sub domain G3 to avoid reflections back to the delay line [3]. A receiver IDT is a single electrode assumed to be mass less is attached to the edge of the delay line. Any delay or attenuation caused by sensing film can be inferred from the SAW displacement amplitude recorded at point p (see figure 3). To analyze propagation of SAW waves over the delay line, transient analysis of the SAW delay line is performed using direct solver SPOOLES available in COMSOL Multiphysics [11] with a time interval of 0.1 ns for 12 ns for 100 MHz 1 V peak to peak(V_{in}) input sine wave.

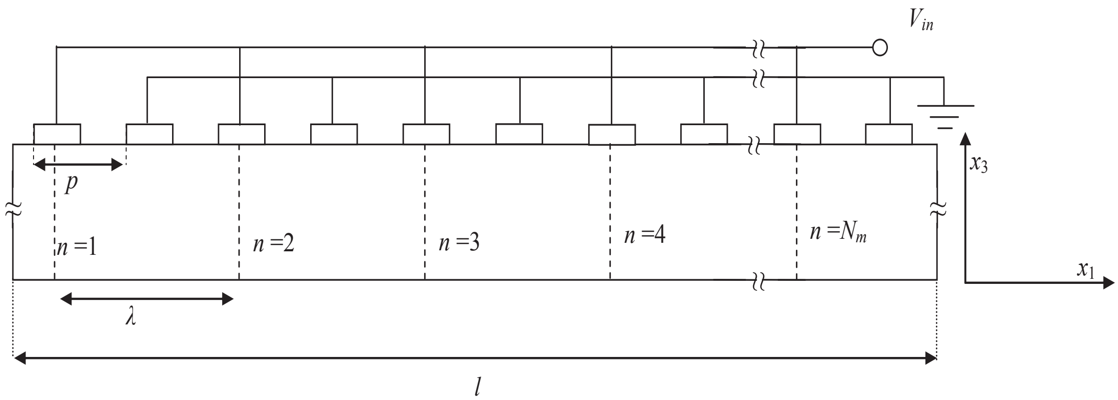


Fig. 2. A Typical IDT with 5 pairs of electrodes.

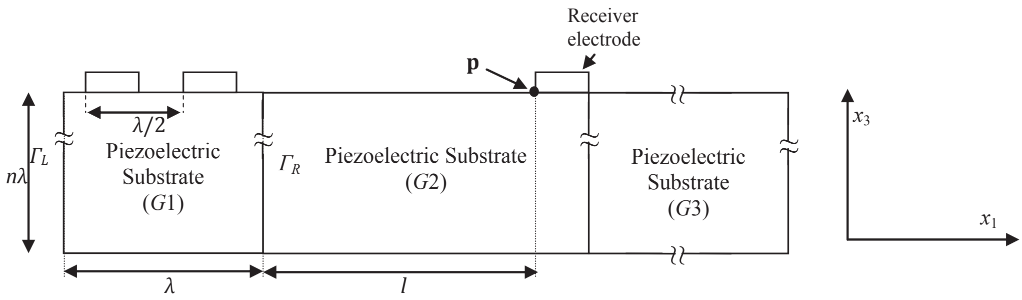


Fig. 3. SAW delay line structure considered for simulation

3. Results and Discussions

In the first stage, time domain analysis is performed only for the SAW transmitter ($G1$, see figure 3) alone and the solutions (displacement and potential) of the transmitters. In the second stage the computed DOF for the boundary (Γ_R) is provided as input to the delay line and simulation of the delay line alone is performed (G_2 and G_3, see figure 3).

The displacement amplitude along x_1 and x_3 at the transmitter, delay line and receiver electrode are recorded for every time t. The total displacement of the propagating SAW (along x_3) over the delay line after 100 ns is shown in fig. 4 (a). Fig. 4 (b) shows vertical displacement amplitude (displacement along x_3) recorded at the edge of transmitting IDT. It can be noted that the maximum displacement amplitude along x_3 at the transmitter IDT is $3.8\text{x}10^{-11}$ m. As the transmitting IDT simulates an IDT with 5 finger pairs and the input potential applied to the IDT is a continuous sinusoidal wave, the amplitude attains stability from the fifth cycle. Fig. 4 (c) shows the recorded displacement amplitudes of the SAW at point **p** (see fig. 3) of delay line. It can be noted that the displacements along x_3 and x_1 are out of phase by 90° with amplitude of $2.8\text{x}10^{-11}$ m and $2.1\text{x}10^{-11}$ m, respectively. For a case of transmitter IDT with 5 finger pairs the degrees of freedom to be computed is found to be 26082, by this method it is reduced up to 1377. In case of simulating the total SAW device with transmitter of 5 finger pair and a delay line of two wave lengths the degrees of freedom found to be 58125, by this method it can be reduced up to 16128 and the computational complexity is reduced by 72.25 %

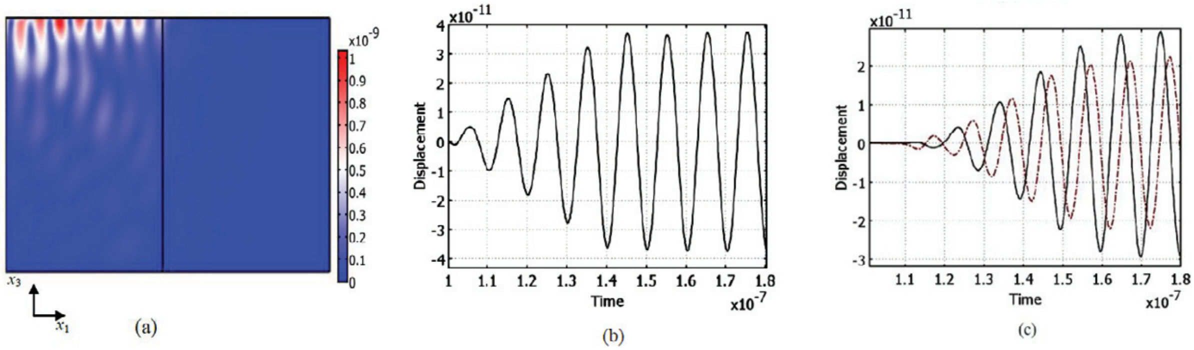
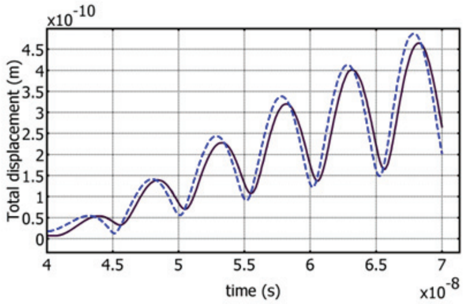
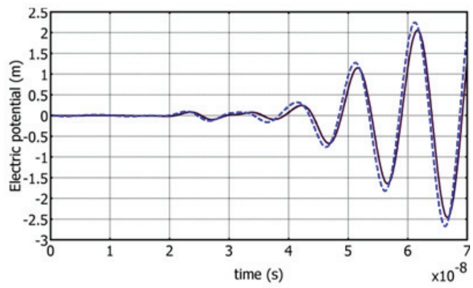


Fig. 4. (a) Profile of total displacement of SAW amplitude over the delay line, (b) Vertical displacement of SAW measured at the edge of the transmitter IDT, (c) Vertical and horizontal displacement of SAW measured at the edge of the delay line.



(a)



(b)

Fig. 5(a). Total displacement of SAW recorded at the receiver point in the presence and absence of hydrogen, Fig. 5 (b) Electric potential of SAW recorded at the receiver point in presence and absence of hydrogen.

Further as an example to show the potential of proposed simulation, an FEM simulation of SAW hydrogen sensor is performed. A palladium thin film is assumed to be coated in the delay line path. The material properties of palladium thin film are provided for the presence of 0 % (without hydrogen) an 3 % hydrogen and time domain analysis of the SAW delay line is performed. The electric potential, total displacement of the SAW for the presence and absence of hydrogen are recorded at point *p* and shown in Fig. 5 (a) and (b). As an outlook from the figures, it is evident that there is a significant attenuation and delay of SAW due to change in properties of the palladium film (for with and without hydrogen). It can be seen that SAW has taken 35 ns to reach the receiver electrode. Further from fig. 5 (b) it can be observed that a delay of 0.45 ns is observed for a presence of 3 % hydrogen when compared to absence of hydrogen.

4. Conclusions

A SAW delay line device is modeled and simulated using COMSOL Multiphysics. The proposed SAW delay line model significantly reduce the number of DOF to solve during FEM simulation, accordingly the computation complexity and memory usage of the machine is considerably reduced. The proposed SAW delay line model for FEM simulation can be extended to simulate a SAW sensor by placing sensing material in the delay line path.

Acknowledgements

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